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14. ABSTRACT

Collaborative research was conducted by the faculty known as the Lithography Network. This network brings together world class researchers over a broad set of technology areas essential to the success of maskless lithography and non-conventional patterning. The primary faculty by task is listed below:
Task 1: Electron Beam Technology for Maskless Lithography, Professor R. Fabian Pease (Coordinator); Task 2: Spatial Light Modulators for Maskless lithography, Professor Olav Solgaard (Coordinator); Professor Andrew Neureuther; Task 3: Maskless Droplet-On-Demand (DoD) Systems. Professor Vivek Subramanian (Coordinator), Professor Jeffrey Bokhor; Task

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lithography, maskless, electron beam, spatial light modulators, drop-on-demand, resists, plasmons, data compression

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Report Title

Innovative Technologies for Maskless Lithography and Non-Conventional Patterning

ABSTRACT

Collaborative research was conducted by the faculty known as the Lithography Network. This network brings together world class researchers over a broad set of technology areas essential to the success of maskless lithography and non-conventional patterning. The primary faculty by task is listed below:
Task 1: Electron Beam Technology for Maskless Lithography, Professor R. Fabian Pease (Coordinator); Task 2: Spatial Light Modulators for Maskless lithography, Professor Olav Solgaard (Coordinator); Professor Andrew Neureuther; Task 3: Maskless Droplet-On-Demand (DoD) Systems. Professor Vivek Subramanian (Coordinator), Professor Jeffrey Bokhor; Task 4: Advanced Materials for Maskless Lithography, Professor C. Grant Willson (Coordinator), Professor Jean Frechet; Task 5: Characterization of Nanoscale Phenomena for Maskless Lithography, Professor Andrew R. Neureuther (Coordinator); Task 6: Data Compression and Path Issues for Maskless Lithography, Professor Avideh Zakhor (Coordinator).

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Index

Title	Page No.
Highlights ……………………………………………………………………..	3
Electron Beam Technology for Maskless Lithography ……………………..	5
Spatial Light Modulators for Maskless Lithography …………………………	7
Maskless Droplet-On-Demand (DoD) Systems ………………………………	9
Data Path Issues for Maskless Lithography ……………………………………	12
Resists …………………………………………………………………………….	14
Modeling Nanoscale Phenomena for Maskless Lithography ……………………	16

Research Highlights

Electron Beam Optics for Lithography and Inspection

The approach described here employs a uniform magnetic field to focus thousands of electron beams simultaneously and operates with unity magnification.

Spatial Light Modulators for Maskless Lithography

Maskless lithography holds tremendous promise for IC production through reduced cost and increased flexibility. In addition to reduced cost, maskless lithography enables linearly-varying phase shifts, and nearly-perfect aligned exposures of different patterns in the same resist layer. This report presents work on the design, fabrication and characterization of SLMs (Spatial Light Modulators) for maskless lithography and demonstration of pattern generation using the SLM in an aerial imaging setup. Line-width modulation, sub-grid placement, and checker-board patterns for the creation of dark lines and spaces were demonstrated. It is shown that through-focus variation and asymmetry can be compensated by multiple aligned exposures. Optical vortices are demonstrated and are shown to have excellent through-focus characteristics and in a final demonstration, it is shown that pixel calibration sensitivity can be improved using a unique configuration of the surrounding mirrors.

Maskless Droplet-On-Demand (DoD) Systems

This project is aimed at scaling the size of droplets produced via droplet-on-demand from nano-apertures for the purpose of directly maskless lithography, and at developing functional materials for direct printing of semiconductors, dielectrics, and conductors for realizing printed electronic structures. MEMS technology was used to fabricate droppers in a visualization system and test them to visualize the droplet generation process, determine droplet size, and find conditions for generation of highly-scaled drops. Simultaneously, a suite of printable nanomaterial semiconductors, dielectrics, and insulators were developed, and used to realize a range of directly printed active components for heterogenous and low-cost electronics integration.

Data Path Issues for Maskless Lithography

Achieving the throughput of one wafer layer per minute with a direct-write maskless lithography system, using 22-nm pixels for 45-nm feature sizes, requires data rates of about 12 Tb/s. A key to achieving such throughput is advanced compression algorithms that allow us to decompress the IC layer at the writers. This project developed a class of novel lossless compression technique specifically tailored to flattened, rasterized, layout data called context copy combinatorial code (C4), which exceeds the compression efficiency of all other existing techniques including BZIP2, 2D-LZ, and LZ77, especially under a limited decoder buffer size, as required for hardware implementation. The team also has developed a variation of the C4 algorithm, called block C4, which lowers the encoding time of C4 by several orders of magnitude, concurrently with lowering the decoder complexity. A variation of Block C4 is currently being implemented on an ASIC to demonstrate it feasibility for practical applications. The authors have developed lossless compression algorithms for hierarchical IC layouts in order to minimize storage and transmission of such files during the IC design and manufacturing process. This is particularly important with OPC processed layouts.

Resists

The goal of this project was to explore materials and methods within the context of self-assembling resist materials that can be patterned using scanning probe lithography. The work has included the study of small molecules as well as dendritic macromolecules capable of self-assembly onto a wafer surface for field induced patterning. In addition the authors have explored the used of common organic solvents such as hexadecane or perfluoroalkanes for the deposition of an etch resistant layer onto a surface under exposure by a scanning probe tip. A photoresist that has high sensitivity without bias would combine the best features of non-chemically amplified resists and chemically amplified resists (CAR). In typical CARs, a photogenerated acid

catalyst diffuses among polymers and reacts with them to achieve gain, but this diffusion also produces bias and blur. Decoupling mass transport from chemical amplification would provide gain without bias. A photosensitive polymeric dissolution inhibitor (PDI) can be utilized to achieve these goals. The PDI material must have the following properties: a low ceiling temperature, a photolabile endgroup, phase compatibility with the resin, dissolution inhibition capabilities of the resin, and a solubility switch once exposed.

Modeling Nanoscale Phenomena for Maskless Lithography

A framework was developed that allows process technologists, device and circuit designers to simultaneously view a product development. It includes layout, OPC, imaging, transistor contours, HSPICE and circuit simulation. A large library of layout test patterns and a web-interfaced database are included for layout screening and experiment validation. A nanoscale feature electromagnetic software suite was developed for analyzing the role of nanoscale structures such a nanotubes and nanoscale phenomena such as plasmons. Various incident plane and plasmon wave sources are used and quantitative data is produced on the local field intensities and scattered plane and plasmon wave amplitudes and phases. This task was jointly funded by SRC and DARPA Advanced Lithography Program under the proposal titled "Innovative Technologies for Maskless Lithography and Non-Conventional Patterning".

Final Report on Distributed-Axis Electron beam optics for Lithography and Inspection

PI: Fabian Pease
Student: Daniel Pickard

The biggest obstacle to the progress of integrated circuit technology is the cost of lithography. There are two main contributions to this cost. One is the cost of extending the resolution of optical lithography beyond the Rayleigh criterion (k1 of ~0.6); the other is the cost of an inspected and qualified photolithographic mask. Electron beam lithography can delineate features 10 nm and smaller, solving the resolution problem without a mask. However, the throughput of electron beam systems is severely limited by space charge which blurs the beam when writing with large currents. One way to overcome this limit is to employ multiple electron optical systems but this has not proved practical because of the difficulty of making a sufficient number of matched columns.

The approach described here employs a uniform magnetic field to focus thousands of electron beams simultaneously and operates with unity magnification. Thus the source must be at least as small as the beam at the wafer. So the first task was to demonstrate the fabrication and operation of a source with a diameter of 50nm or less. Fabrication was accomplished by employing micromachining, including extensive use of a focused ion beam, to fashion an array of apertures of diameter 50nm or less in 800nm platinum. Each aperture can be illuminated by an electron beam larger than the aperture. To prevent the build-up of contamination the beam heats the aperture to an estimated 200C. Successful operation was demonstrated by building a test-bed featuring a region of uniform magnetic field strength up to 0.3T and building, inside this region, a miniature scanning electron microscope (SEM) whose source comprised the above aperture array illuminated with a thermionic gun and whose focusing was entirely by the above magnetic field. We observed values of resolution between 30nm and 50nm at 10kV and better than 75nm at 1kV. This SEM can image at landing energies as low as 260 Volts, bringing out a dramatic improvement in surface contrast. Increasing the magnetic field strength so that the electrons execute many cyclotron orbits reduces the spurious deflection caused by stray fields.

Stitching together the patterns from different beamlets will include acquiring the landing position of each beam using the secondary electron signal from each beamlet. Thus we must detect and separate the secondary electrons generated by adjacent beamlets. Separation is achieved by spacing the beamlets by more than the cyclotron diameter of the secondary electrons. The spacing used, 250 microns, is more than sufficient. Detection of beams separated by 125 microns was demonstrated with a custom-designed and built, monolithic, PIN detector featuring a linear array of 40 detector elements.

The envisaged system requires a sparse array of matched electron sources (to illuminate the aperture array) each modulatable up to 100MHz, with current densities exceeding 10A/cm2, and with an electron energy spread of less than 0.5 eV. Conventional photocathodes have either sufficient quantum efficiency but need impractically good vacua or else they require impractically high light intensities. Two new configurations were investigated. The first, the electron bombardment source (EBS), features a thin semiconductor (single crystal diamond) membrane with a negative electron affinity (NEA) emission surface. Free carriers within the membrane are generated by high-energy electrons impinging on the back surface. We demonstrated the first scanning electron microscope images employing this cathode.

In the second configuration the incident optical field is coupled to surface plasmon-polaritons in a metallic film and should yield a quantum efficiency two orders of magnitude larger than that of conventional photoemission from a metallic film. A conservative estimate of the performance of a configuration featuring a magnesium-coated, edge-polished, single-mode fiber yields a current density of 30 A/cm2 per milliwatt when surface plasmons are excited with a HeCd (325 nm) laser.

While the initial motivation for our approach was lithography, our system is not limited to this application; the obvious extension to high-speed inspection of both wafers and masks is one obvious alternative and shares many of the system attributes.

The full description of this work is to appear as the PhD dissertation of Daniel Pickard which is in the final stages of preparation (the PI has already approved the bulk of it) and should be available for the sponsors at the end of March 2006.

Task Title: Maskless Lithography
Task I.D.: 460.009
Sponsor Ref.: SA4841-78134
Sub Task: Spatial Light Modulators for Maskless Lithography

- **Deliverable Title:** Final Report on the design, fabrication, and experimental verification of a MEMS SLM with linearly varying phase. Demonstration of isolated-feature aerial images through phase singularities (optical vortices).

Task Leader: Olav Solgaard, Stanford University, CA 94305-4075 solgaard@stanford.edu
Andrew Neureuther, UC Berkeley, CA 94720-1770 neureuth@eecs.berkeley.edu

Abstract:

Maskless lithography holds tremendous promise for IC production through reduced cost and increased flexibility. In addition to reduced cost, maskless lithography enables linearly-varying phase shifts, and nearly-perfect aligned exposures of different patterns in the same resist layer. This report presents work on the design, fabrication and characterization of SLMs (Spatial Light Modulators) for maskless lithography and demonstration of pattern generation using the SLM in an aerial imaging setup. Line-width modulation, sub-grid placement, and checker-board patterns for the creation of dark lines and spaces were demonstrated. It is shown that through-focus variation and asymmetry can be compensated by multiple aligned exposures. Optical vortices are demonstrated and are shown to have excellent through-focus characteristics and in a final demonstration, it is shown that pixel calibration sensitivity can be improved using a unique configuration of the surrounding mirrors. This task was jointly funded by SRC and DARPA Advanced Lithography Program under the proposal titled "Innovative Technologies for Maskless Lithography and Non-Conventional Patterning".

Original Objectives

- Development of practical micromachining technologies that enable fabrication of large arrays (>3,000 by 3,000) and small pixels (~20um by 20um) that can tilt on two orthogonal axes and move vertically for linear phase-shift control.
- Investigate the potential advantages of fast, "self-aligned" multiple exposures with optimized illumination that are enabled by MEMS SLMs.
- Explore interferometric-voting self-calibration of the SLMs.
- Demonstration of isolated-feature aerial images through phase singularities (optical vortices).

Significant changes in direction

- Through theory and simulations, SLM pixels that move vertically were shown to have better performance to tilting mirrors and hence vertical actuation mirrors were designed and fabricated.

Most significant outcomes and deliverables, especially software

- Design, fabrication and characterization of a SLM (Spatial Light Modulator) and verification of strong phase-shifting capabilities through demonstration of pattern generation with aerial imaging experiments.
- Demonstration of pattern generation such as dark lines and spaces using an individually addressable array, dense rows/columns, and checkerboard configuration of pixels.
- Demonstration of linewidth modulation and sub-grid placement capability.

- Demonstration of "self-aligned" multiple exposures to compensate for through-focus variation and asymmetries.
- Demonstration of an optical vortex and its excellent through-focus characteristics.
- Demonstration of improvement in pixel calibration sensitivity using a unique configuration of the surrounding of mirrors for self-calibration improvement of a maskless system.

Possible Patentable Innovations/Results

- Interferometric-voting self-calibration scheme.
- Process window improvements through the use of "self-aligned" multiple-exposures.

Participating students

Il Woong Jung, Jen-Shiang Wang

Most significant publications

1. I. W. Jung, J. S. Wang, O. Solgaard, "Vortex Generation and Pixel Calibration Using a Spatial Light Modulator for Maskless Lithography," IEEE/LEOS International Conference on Optical MEMS and Nanophotonics, Hualien, Taiwan, August 12-16, 2007.
2. I. W. Jung, J. S. Wang, O. Solgaard, "Optical Pattern Generation Using a Spatial Light Modulator for Maskless Lithography," IEEE Journal of Selected Topics in Quantum Electronics, Vol. 13, Issue 2, pp. 147-154, March-April 2007.
3. I. W. Jung, J. S. Wang, O. Solgaard, "Spatial Light Modulator for Maskless Lithography," IEEE/LEOS International Conference on Optical MEMS, Big Sky, Montana, USA, pp. 150-151, August 21-24, 2006.

Significant references and resources i.e., group Web sites

Solgaard group website:
http://www.stanford.edu/group/SML/research.html#maskless

Future directions

- N/A

Task Title: Maskless Lithography
Task I.D.: 460.010
Sponsor Ref.: n/a
Sub Task: Maskless Droplet-on-Demand (DoD) Systems
Deliverable Title: Final Report on Research Accomplishments and Future Direction

Task Leader: Jeff Bokor, UC Berkeley, CA 94720-1770 jbokor@eecs.berkeley.edu
Vivek Subramanian, UC Berkeley, CA 94720-1770 viveks@eecs.berkeley.edu

Abstract:

This project is aimed at scaling the size of droplets produced via droplet-on-demand from nano-apertures for the purpose of directly maskless lithography, and at developing functional materials for direct printing of semiconductors, dielectrics, and conductors for realizing printed electronic structures. MEMS technology was used to fabricate droppers in a visualization system and test them to visualize the droplet generation process, determine droplet size, and find conditions for generation of highly-scaled drops. Simultaneously, a suite of printable nanomaterial semiconductors, dielectrics, and insulators were developed, and used to realize a range of directly printed active components for heterogenous and low-cost electronics integration.

Original Objectives
The result of droplet-on-demand (DoD, or "inkjet") printing research will be a scientific and technological foundation for the eventual development of commercial systems that can directly deposit functional materials (semiconductors, dielectrics, and low-resistance conductors) with scaling of printing resolution to the nano regime (<50 nm).
Significant changes in direction

Most significant outcomes and deliverables, especially software

- Thermal bubble actuation of inkjet printheads was found to reach a scaling limit of ~1 micron droplet diameter due to limitations of the maximum pressure that could be generated by boiling the liquid ink.
- Evaporation of the droplet solvent during flight was found to be a viable method for shrinking the droplet. Controllable shrinkage of the droplet by about a factor of 3 was demonstrated.
- Thermal bubble actuation was also found to have a significant drawback when used with nanoparticle based inks in that the heating of the ink led to aggregation of the nanoparticles leading to deposition on the heater as well as nozzle clogging. For this reason, it was determined that another actuation method would be required. A PZT-based membrane actuator scheme was identified.
- Simulations and design studies indicate that a PZT membrane actuator based inkjet head could produce droplets with diameter approaching 100 nm diameter.
- Preliminary fabrication results for sol-gel deposited PZT films showed good morphology and the proper stoichiometry and perovskite phase.
- A suite of nanoparticle-based conductor inks were developed for direct forming of printed high-conductivity conductors, with peak process temperatures of <150°C.
- Printed conductors, semiconductors, and dielectrics were integrated to demonstrate world-record performance printed organic transistors and diodes on plastic.

- The potential for heterogenous integration was demonstrated by using droplet-on-demand techniques to realize novel electronic-nose-based gas sensors and electrically read DNA microarray systems.

Participating students
Yan Wang
Nathan Emley
Qintao Zhang
Daniel Huang
Lakshmi Jagannathan

Most significant publications

1. Wang, Y., Bokor, J., and Lee, A. "**Maskless lithography using drop-on-demand inkjet printing method,**" Proc. SPIE ***5374,*** p. 628-636, 2004.
2. Wang, Y., and Bokor, J. **"Ultra-high-resolution monolithic thermal bubble inkjet print head,"** J. Micro/Nanolith. MEMS MOEMS **6,** 043009 (2007)
3. Zhang, Q, and Subramanian, V **"DNA hybridization detection with organic thin film transistors: Toward fast and disposable DNA microarray chips"**, Biosensors and Bioelectronics, 22, pp. 3182-3187, 2007.
4. V. Subramanian, P.C. Chang, J. B. Lee, S. E. Molesa, S. K. Volkman **"Printed organic transistors for ultra-low-cost RFID applications"** , IEEE Transactions on Components & Packaging Technologies, vol. 28, pp. 742-727, 2005.
5. Vivek Subramanian, Jean M. J. Fréchet , Paul C. Chang, Daniel Huang, Josephine B. Lee, Steven E. Molesa, Amanda R. Murphy, David R. Redinger, and Steven K. Volkman **"Progress towards development of all-printed RFID tags: Materials, Processes, and Devices"**, Proceedings of the IEEE, vol. 93, pp. 1330-1338, 2005.
6. F. Liao, C. Chen, and V. Subramanian **"Organic TFTs as gas sensors for electronic nose applications",** Sensors and Actuators B-Chemical. Vol. 107, pp. 849-855, 2005.
7. Zhang, Q, and Subramanian, V **"Label-free low-cost disposable DNA hybridization detection systems using organic TFTs"**, 2007 IEEE International Electron Device Meeting, Washington DC, Dec 10-12, 2007.
8. Zhang, Q, and Subramanian, V **"Printable DNA sensor using organic transistors"**, Transducers 2007, Lyon, France, 3EH5.P, 2007.
9. D. Huang and V. Subramanian **"Iodine-doped pentacene schottky diodes for high-frequency RFID rectification"**, 2006 IEEE Device Research Conference, June 2006.
10. S. E. Molesa, A. de la Fuente Vornbrock, P. C. Chang, V. Subramanian **"Low-Voltage Inkjetted Organic Transistors for Printed RFID and Display Applications"**, IEEE International Electron Device Meeting Technical Digest, pp. 5.4.1-5.4.4, 2005.
11. Steven E. Molesa, Steven K. Volkman, David R. Redinger, Alejandro de la Fuente Vornbrock, and Vivek Subramanian **"A high-performance all-inkjetted organic transistor technology"**, 2004 IEEE International Electron Device Meeting Technical Digest, pp. 1072, 2004.

Significant references and resources i.e., group Web sites

http://organics.eecs.berkeley.edu

Future directions

- Complete fabrication of PZT actuated printheads and push droplet diameter down to 100 nm scale.
- Development of electronic functional inks based on nanomaterials for realization of application of droplet-on-demand to semiconductor packaging, electronics on plastic, and heterogenous integration.

Task Title: Maskless Lithography
Task I.D.: 460.011
Sponsor Ref.: n/a
Sub Task: Data Path Issues for Maskless Lithography
Deliverable Title: Final Report on compression of hierarchical and rasterized IC layout files

Task Leader: Avideh Zakor, UC Berkeley, CA 94720-1770 avz@eecs.berkeley.edu
Borivoje Nikolic, UC Berkeley, CA 94720-1770 bora@eecs.berkeley.edu

Abstract:

Achieving the throughput of one wafer layer per minute with a direct-write maskless lithography system, using 22-nm pixels for 45-nm feature sizes, requires data rates of about 12 Tb/s. A key to achieving such throughput is advanced compression algorithms that allow us to decompress the IC layer at the writers. In this project, we developed a class of novel lossless compression technique specifically tailored to flattened, rasterized, layout data called *context copy combinatorial code (C4)*, which exceeds the compression efficiency of all other existing techniques including BZIP2, 2D-LZ, and LZ77, especially under a limited decoder buffer size, as required for hardware implementation. We have also developed a variation of the C4 algorithm, called block C4, which lowers the encoding time of C4 by several orders of magnitude, concurrently with lowering the decoder complexity. A variation of Block C4 is currently being implemented on an ASIC to demonstrate it feasibility for practical applications. We have also developed lossless compression algorithms for hierarchical IC layouts in order to minimize storage and transmission of such files during the IC design and manufacturing process. This is particularly important with OPC processed layouts. This task was jointly funded by SRC and DARPA Advanced Lithography Program under the proposal titled “Innovative Technologies for Maskless Lithography and Non-Conventional Patterning”.

Original Objectives

- Develop lossless compression algorithms for rasterized IC layouts with applications to direct write lithography systems.
- Develop lossless compression algorithms for hierarchical IC layouts with applications to file handling, storage and transmission.

Significant changes in direction

- Also investigated the problem of speeding up model based OPC using machine learning algorithms.

Most significant outcomes and deliverables, especially software

- Two patents: one on hierarchical IC Layout compression and one on applying machine learning techniques to speed up model based OPC

Participating students
- Cindy Liu (graduate student)
- Vito Dai (graduate student)

- Alan Gu (graduate student)
- Peiran Gao (undergraduate student)

Most significant publications

- H. Liu, V. Dai, A. Zakhor and B. Nikolic, **"Reduced Complexity Compression Algorithms for Direct-Write Maskless Lithography Systems,"** *SPIE Journal of Microlithography, MEMS, and MOEMS (JM3)*, Vol. 6, 013007, Feb. 2, 2007.
- Gu and A. Zakhor, "Lossless Compression Algorithms for Hierarchical IC Layout", accepted for publication at IEEE Transactions on Semiconductor manufacturing, November 2007; also in the Proceedings of SPIE, Vol. 6520, Optical Lithography XX, pp. 652017-1 to 652017-17, Feb. 2007.
- V. Dai and A. Zakhor, **"Lossless Compression of VLSI Layout Image Data,"** *IEEE Trans. on Image Processing*, Vol. 15, Issue 9, Sept. 2006 , pp. 2522-2530
- P. Gao, A. Gu, and A. Zakhor, **"Optical Proximity Correction with Principal Component Regression,"** Optical Microlithography XXI, Proceeding of SPIE, San Jose, California, Vol. 6924, February 2008.
- H. Liu, V. Dai, A. Zakhor and B. Nikolic, **"Reduced Complexity Compression Algorithms for Direct-Write Maskless Lithography Systems"**, Emerging Lithographic Technologies X, Proceedings of SPIE, San Jose, California, Vol. 6151, 61512B-12, March 2006.
- V. Dai and A. Zakhor, **"Complexity Reduction for C4 Compression for Implementation in Maskless Lithography Datapath",** in Emerging Lithographic Technologies IX, Proceedings of the SPIE, San Jose, California, Vol. 5751, March 2005.
- V. Dai and A. Zakhor, **"Advanced Low-complexity Compression for Maskless Lithography Data"** in *Emerging Lithographic Technologies VIII*, Proceedings of the SPIE, San Jose, California, Vol. 5374, No. 1, February 2004, pp. 610-618.

Significant references and resources i.e., group Web sites

- Zakhor's group web site: httpe://www-video.eecs.berkeley.edu

Future directions

- Complete ASIC implementation of Block C4 and test it.
- Participate in the direct write lithography system development work by DARPA.

Task Title: Maskless Lithography
Task I.D.: 460.012
Sponsor Ref.: SA4940-78134
Sub Task: Resists
Deliverable Title: Final Report on gain without bias
Task Leader: Grant Willson, U of Texas, TX 78713-7159 willson @che.utexas.edu
Jean J. M. Frechet, UC Berkeley, CA 94720-1460 frechet@.berkeley.edu

Abstract:

The goal of this project was to design a photoresist that has high sensitivity without bias. This formulation would combine the best features of non-chemically amplified resists and chemically amplified resists (CAR). In typical CARs, a photogenerated acid catalyst diffuses among polymers and reacts with them to achieve gain, but this diffusion also produces bias and blur. Decoupling mass transport from chemical amplification would provide gain without bias.

A photosensitive polymeric dissolution inhibitor (PDI) can be utilized to achieve these goals. The PDI material must have the following properties: a low ceiling temperature, a photolabile endgroup, phase compatibility with the resin, dissolution inhibition capabilities of the resin, and a solubility switch once exposed. This task was jointly funded by SRC and DARPA Advanced Lithography Program under the proposal titled “Innovative Technologies for Maskless Lithography and Non-Conventional Patterning”.

Original Objectives

- Explore the design of new resist systems that decouple chemical amplification and image blur

Significant changes in direction

- New monomer synthesis
- New photolabile end groups

Most significant outcomes and deliverables, especially software

- Synthesized and polymerized aldehyde and styrenic monomers
- Demonstrated ability to both initiate and end-cap polymers with photolabile end-groups
- Showed control of molecular weight to achieve phase compatibility
- Demonstrated dissolution inhibition capabilities of both aldehyde and styrenic PDIs
- Synthesized first non-crystalline amorphous poly(aliphatic aldehyde)
- Fabricated features showing proof of concept
- Carried out photochemical investigations of PDIs

Participating students

- Graduate:
  Jeff R. Strahan, Jacob R. Adams, Brian K. Long
- Undergraduate:
  Tim Rochelle, Colin Neikirk, Will Durand

Most significant publications

Johnson, Heather F.; Ozair, Sahban N.; Jamieson, Andrew T.; Trinque, Brian C.; Brodsky, Colin C.; Willson, C. Grant. "Cationic graft polymerization lithography." Proc. SPIE, 5037, 943-951, (2003).

Pawloski, Adam R.; Acheta, Alden, Levinson, Harry J.; Michaelson, Timothy B.; Jamieson, Andrew; Nishimura, Yukio; Willson, C. Grant. "Line Edge Roughness and Intrinsic Bias for Two Methacrylate Polymer Resist Systems," J. Microlith., Microfab., Microsyst. 5(2), pp. 023001-1 through 023001-16 (2006).

Significant references and resources i.e., group Web sites

- Willson group website: http://willson.cm.utexas.edu/

Future directions

- **Continue to work on the new amorphous poly(aliphatic aldehyde) and determine its PDI capabilities**
- **Continue to work on styrenic PDIs**

Task Title: Maskless Lithography
Task I.D.: 460.013
Sponsor Ref.: n/a
Sub Task: Modeling Nanoscale Phenomena for Maskless Lithography

- **Deliverable Title:** Final Report on Modeling Nanoscale Phenomena for Maskless Lithography

Task Leader: Andrew Neureuther, UC Berkeley, CA 94720-1770 neureuth@eecs.berkeley.edu

Abstract:

A framework was developed that allows process technologists, device and circuit designers to simultaneously view a product development. It includes layout, OPC, imaging, transistor contours, HSPICE and circuit simulation. A large library of layout test patterns and a web-interfaced database are included for layout screening and experiment validation.

A nanoscale feature electromagnetic software suite was developed for analyzing the role of nanoscale structures such a nanotubes and nanoscale phenomena such as plasmons. Various incident plane and plasmon wave sources are used and quantitative data is produced on the local field intensities and scattered plane and plasmon wave amplitudes and phases.

This task was jointly funded by SRC and DARPA Advanced Lithography Program under the proposal titled “Innovative Technologies for Maskless Lithography and Non-Conventional Patterning”.

Original Objectives

- An integrated engineering framework for assessing the role of pattern, maskless multiple exposures fracture, resist materials, PEB-treatments, and pattern transfer on Line-Edge-Roughness and device performance.
- Engineering understanding of nanoscale material phenomena in carbon nanotubes, plasmons, resist inhomogenities and their impact on maskless lithography.
- Characterization of key issues in Plasmon based light and electron collectors, polarizer for high-NA.

Significant changes in direction

Due to the concern of industry with process variation at the higher level of design the research emphasis shifted to exploring new infrastructure methodologies for linking process and design via prototype development. The work on random resist contributions to LER was picked up by DARPA in a shot-noise study that used e-beam exposure of contacts and concluded that the effective shot-noise effect was a contribution of resist dissolution and not exposure phenomena. The work on methodologies for characterizing process variations was synergistically enhanced by close collaboration with an industry and State of California supported research program on Feature Level Compensation and Control. In particular, it was possible to create multi-student test masks, plan single level, NMOS and enhanced-NMOS experiments at Cypress Semiconductor and SVTC, and get electrical test data on single layers for verification of the Collaborative Platform for DfM.

Due to limited resources the work on electromagnetic modeling was carried out in conjunction with application work for JPL on vector simulation of pupil plane mask edge effects.

Most significant outcomes and deliverables, especially software

A first of its kind Collaborative Platform for DfM software framework was developed through the PhD thesis work of Wojtek Poppe that allows process technologists, device technologists and circuit designers to simultaneously view a product development in terminology common to each special expertise. The framework is modular and allows combinations of commercial or university CAD tools to work from layout, to OPC, image simulation, contour extraction, nonuniform transistor modeling with BSIM, HSPICE deck creation and circuit simulation. A large library of single layer, NMOS and enhanced-NMOS electrical test structures for evaluating process susceptibility and process monitoring capabilities is also available. An accompanying web-interfaced database can be used to make extensive process susceptibility screening studies of layouts and compare with electrical testing of silicon across multiple user contributed layouts.

A first of its kind nanoscale feature electromagnetic software suite was developed through the PhD thesis work of Dan Ceperley for analyzing the role of nanoscale structures such a nanotubes and nanoscale phenomena such as plasmons. The Finite-Difference Time-Domain software TEMPEST version 7 uses a Device Under Test approach with various incident plane and plasmon wave sources to quantify the local field intensities and scattered plane and plasmon wave amplitudes and phases. The level of nanoscale effects such as plasmons was shown to be quite small for applications in lithography but the local field concentrations of 100-1000 are important in applications such as surface enhanced Raman scattering.

Possible Patentable Innovations/Results

- Interferometric-voting self-calibration scheme (joint with Stanford see 460 task 9).

Participating students

Dan Ceperley (PhD expected May 2008)
Wojtek Poppe (PhD Dec 2008)
Scott Hafeman (MS 2005 returned to Canada)

Most significant publications

Wojtek J. Poppe, Luigi Capodieci, Andrew Neureuther, ”Platform for collaborative DFM”, Proc. SPIE Vol. 6156, 61560E, Mar 2006.

Wojtek J. Poppe, Luigi Capodieci, Joanne Wu, Andrew Neureuther, “From poly line to transistor: building BSIM models for non-rectangular transistors,” Proc. SPIE Vol. 6156, 61560P, Mar 2006.

W. J. Poppe, J. A. Holwill, P. D. Friedberg, L. Alarcon, L. Pang, Q. Liu, A. R. Neureuther, “Transistor-based electrical test structures for lithography and process characterization,” SPIE [6520-142] March 2007.

W. Poppe and A. R Neureuther, D. Jayasuriya, P. Au, “Database and Data Analysis Strategy for Multi-Designer Testchips”, SPIE, Monterey CA Sept 18th, 2007 SPIE BACUS 2007, to appear.

A.R. Neureuther, W. Poppe, J. Rubenstein, E. Chin, L. Wang, J-S Yang, M. Miller, D. Ceperley, C. Clifford, K. Kikuchi, J. Choi, D. Dornfeld, P. Frieberg, C. Spanos, J. Hoang, J. Chang, J. Hsu, D. Graves and M. Lieberman, “Collaborative Platform, Tool-Kit, and Physical Models for DfM,” SPIE Proc. 6521, 2007.

Andrew R. Neureuther and Daniel Ceperley, “ Modeling and Simulation for Nanometrics,” J. Vac Sci. Technol., Vol. 23, pp. 2578-2583, Nov. 2005.

Jen-Shiang Wang, Olav Solgaard, Andrew R. Neureuther, “High-sensitivity interferometric schemes for ML2 micromirror calibrations,” Proc. SPIE Vol. 6151, 615112, Mar 2006.

Significant references and resources i.e., group Web sites

eecs.berkeley.edu/Faculty/Homepages/neureuther.html
The above URL is to Professor Neureuther’s web site which will contain links to home web pages for the “Collaborative platform for DfM” and “TEMPEST ver. 7.” In addition the software and libraries will be uploaded to the SRC web site. It is our intention to encourage further development of both the DfM and TEMPEST software suites by making them open source such as for other universities.

Future directions

Work on the Collaborative Platform for DfM concepts and capability has both seeded new ideas and provided a tool for process aware work. On industry and State of California funding in a new proposal titled Integrated Modeling, Process and Computation for Technology (IMPACT) it will be possible produce and electrically test silicon for the enhanced-NMOS experiment and a follow on CMOS experiments over the next 2 years. Heavy use of the Collaborative Platform for DfM is also being made to understand process effects on circuits designed at the Berkeley Wireless Research Center and fabricated by ST Microelectronics under 90 nm design rules and emerging 45 nm design rules. The Collaborative Platform for DfM is also being used to select focus and dose sensitive circuits and develop scan-chain ring-oscillator process monitors. On SRC 1443 funding, the platform is being used to evaluate circuit performance effects at ‘hot-sots’ and cell-to-cell process interactions identified by fast-CAD pattern matching methods.

The code and user guide for TEMPEST ver. 7 will be released in Q3 2008 under continuing support from IMPACT. It is currently being tested on a diverse set of applications. This in includes collaboration with Mary Peckerar, Maryland, on plasmonic dot-matrix projection printing masks, Mosong Cheng, Texas, A&M, on intermediate near-field plasmonic lens, and Harry Sewell, ASML, on plasmon effects. Studies have also been made at Berkeley of plasmonic particle near fields, color filters, and pattern dependent polarization coupling in off-axis IR laser annealing. Near field amplitude simulations were also included in a white paper in response to a DARPA solicitation for structures to achieve a 10^{12} factor in Surface Enhanced Raman Scattering.